High-Power Electromagnetics (HPEM)

From the 1960s into the 21st Century

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Abstract— **HPEM is a catch-all acronym that includes many electromagnetic waveforms such as natural lightning, nuclear electromagnetic pulse (NEMP), high-power microwaves (HPM), moderate band signals and hyperband transients [1]. With the exception of natural lightning which has existed from time immemorial, the scientific discipline of HPEM started in the 1960s, when serious attention was paid to NEMP. Dr. Carl Baum played a key role in the evolution of HPEM [2]. In this paper, we will review some major milestones of this evolution and also attempt to look ahead.**

Keywords-HPEM, lightning, NEMP, HPM, short pulse, narrowband, moderate band, hyperband

I. INTRODUCTION

Prior to the world's first atomic test in Alamogordo, NM, USA on July 16, 1945, Nobel laureate physicist Enrico Fermi tried to calculate the possible electromagnetic fields that would be produced from the nuclear explosion. This can be conidered as the birth of the study of HPEM.

II. MAJOR MILESTONES OF HPEM

Major Milestones of HPEM, especially in the last 5 decades can be summarized as follows.

1945	TRINITY - Fermi's attempt to estimate NEMP
1951-1962	Additional nuclear tests and measurements (crude compared to today's standards)
1962	Partial Test Ban Treaty (PTBT)
1962–1990	Underground tests, development of EMP simulators and sensors
1978	First NEM meeting, followed every even year Special Issue on NEMP in IEEE Transactions on AP-S and EMC
1980-1989	Special Issues in IEEE Journals on Lightning, HPM, EMP 201 (short course); HPEM technical sessions in various meetings, URSI Statement
1990	URSI Comm E, forms a HPEM working group
1993	IEC issues 61000-2-9 - Radiated HEMP Env.
1994	EUROEM Conference in France
1995	High-Power Short Pulse (IRA) technology development
1996	Russian Scientists participate in AMEREM 1996
1999	URSI Statement on IEMI
2004	U.S. Congressional Committee publishes its first Report on EMP [3]
2004	Special Issue on IEMI in IEEE Trans on EMC [4]
2008	EMP Commission report on threats to Critical Infrastructures [5]

The first decade of the 21st century has seen real and anecdotal evidence of RF Terrorism and IEMI [6].

III. A LOOK AHEAD

Compact HPEM source/antenna systems are commercially available. Developments in pulse-power technologies driving conventional and newer RF devices will lead to improved and more powerful source/ antenna systems. An EMP attack is an example of RF terrorism by rogue countries and non-state actors, and the national infrastructure can be at risk. Infrastructure is a hyper system or a system of systems such as electric power, telecommunication, banking & finance, energy, transportation, food, water, emergency, space, and Government [5]. In addition, cyber threats from hostile governments, terrorist groups and disgruntled employees are on the increase as well. It is prudent for civilized societies to asses such threats and take pro-active and precautionary actions. As an example, if someone had foreseen a threat scenario wherein commercial airliners can be turned into missiles by hijackers, perhaps Nine-Eleven could have been avoided. In the case of Nine Eleven, the pro-active step would have been to install bullet-proof cockpit doors to deny entry to unauthorized persons.

References

[1] D. V. Giri and F. M. Tesche, "Classification of Intentional Electromagnetic Environments (IEME), *IEEE Trans. EMC*, Aug. 2004,

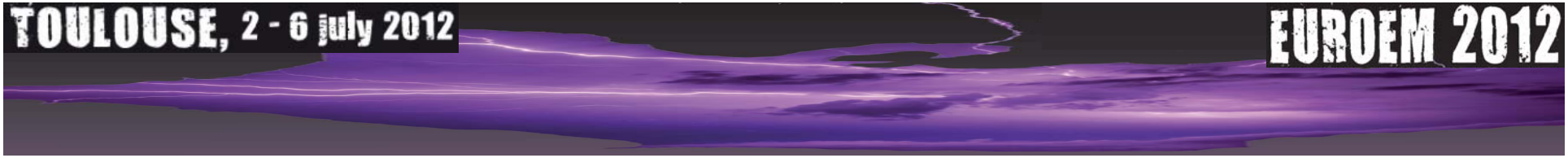
[2] C. E. Baum, "Reminiscences of High-Power Electromagnetics", *IEEE Trans. EMC*, May 2007, pp 211-218.

[3] W.R. Graham (Chairman, EMP Commission) et al., "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack," Volume 1, Executive Report, 2004.

[4] "Special Issue on High-Power Electromagnetics (HPEM) and Intentional Electromagnetic Interference (IEMI)," IEEE Transactions on EMC, Vol. 46, No. 3, August 2004.

[5] W.R. Graham (Chairman, EMP Commission) et al., "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack – Critical National Infrastructures", April 2008.

[6] F. Sabath, "What can be learned from Documented Intentional Electromagnetic Interference (IEMI) Attacks", presented at the International URSI XXX General Assembly, Istanbul, Turkey, 13-20 August 2011.



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Presented at

Plenary Session

EUROEM 2012

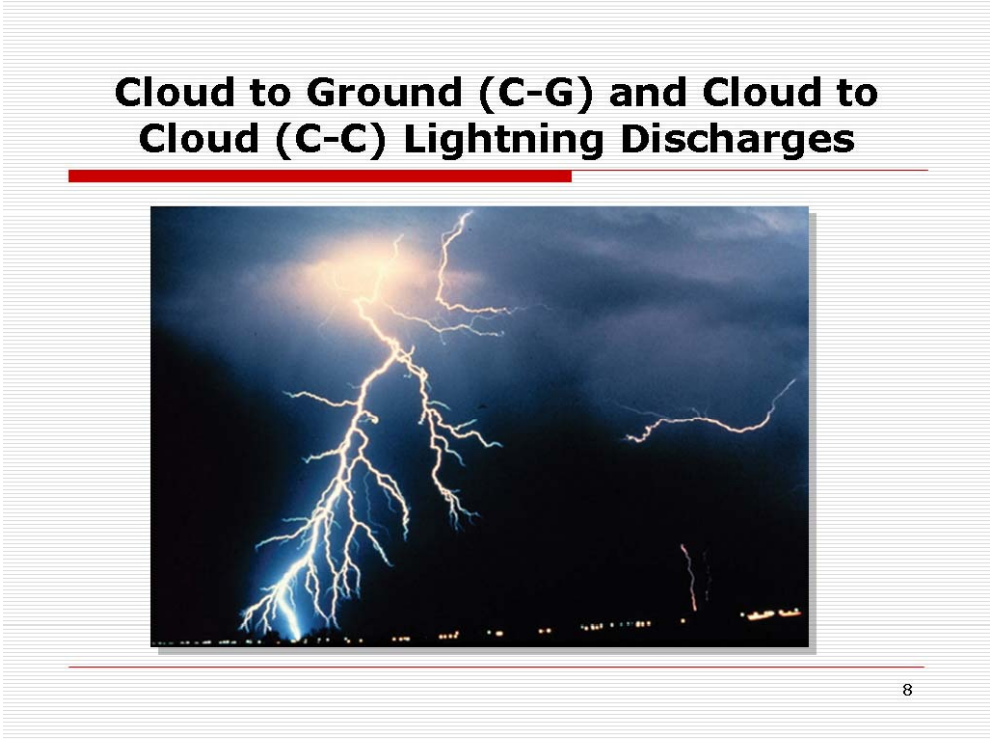
Pierre Baudis Conference , Toulouse, France

4 July, 2012

This presentation is dedicated to the Memory of Dr. Carl E. Baum

1940 - 2010

Time History of HPEM



- **Natural Lightning observable and measurable**

known and unknown effects on people, animals, buildings, airplanes etc.

HPEM made (by nature) has always been there.

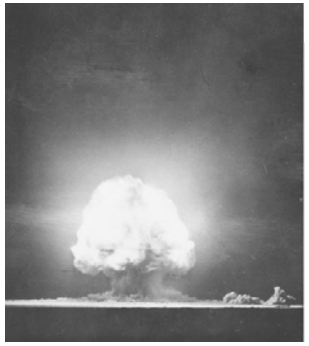
F-106B (NASA 816) research aircraft during Storm Hazards Program (SHP) in 1982

Incident field Sensor

on

Pitot-static tube

PAINT SPOTS APPLIED TO AIRCRAFT THAT DENOTE LIGHTNING ATTACHMENT POINTS



HPEM – Produced by Mankind

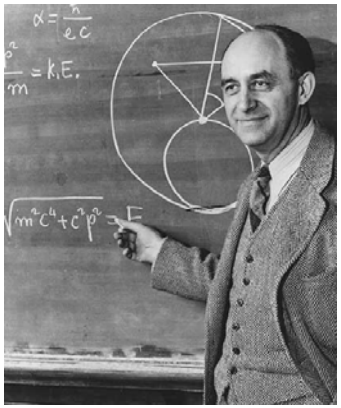
July 1945

- **World's first atomic test in Alamogordo, NM, USA on July 16, 1945**

VIDEO AVAILABLE ON YOU-TUBE !
http://video.google.com/videoplay?docid=8628153120833224911

Nobel laureate physicist Enrico Fermi tried to calculate the possible electromagnetic fields that would be produced from the nuclear explosion.

Can be considered as the birth of the study of HPEM.



1945 to 1962

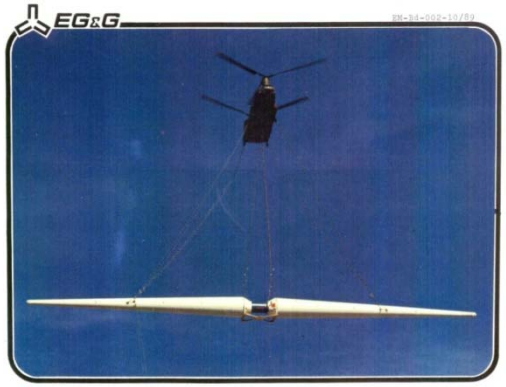
1945 TRINITY - Fermi's attempt to estimate NEMP

1951-1962 Additional nuclear tests and measurements (crude compared to today's standards)

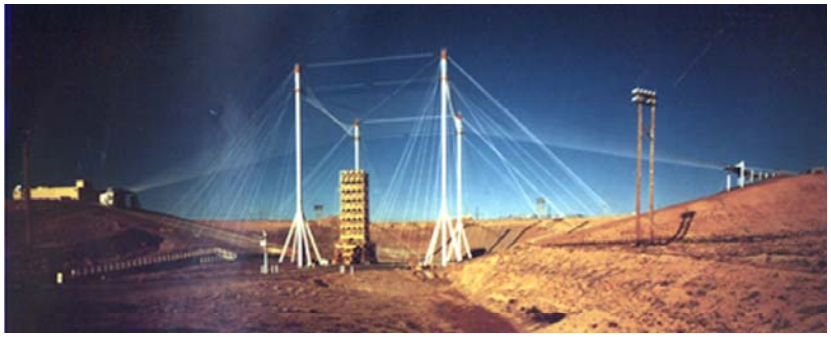
1962 USA, USSR and UK ratify Limited Test Ban Treaty (LTBT) President Kennedy signing in the White House.

1962 - 1990

3 Decades of Development of NEMP Simulators and Sensors

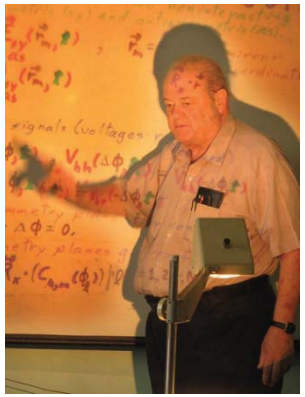


RES



ARES –Guided wave – 40m high

ATHAMAS I - Hybrid



Dr. C. Baum

ATLAS I – World's largest - Radiating

1975 - I came to work with Carl at AFWL (now called AFRL, KAFB, NM

1978

First NEM meeting, followed every even year - EUROEM 2012 is the 18th Meeting in this series

Special Issue on NEMP in IEEE Transactions on AP-S and EMC

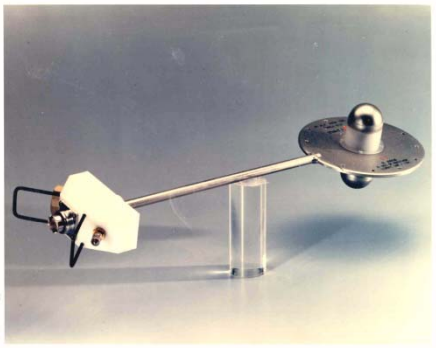
NEMP Simulators and Sensors

EMPRESS II (Radiating)

1983

First EMP 201 (short course) by Dr. Baum Socorro, NM

Swiss VERIFY – sub ns



Free Field D-dot sensor

F5 “Tiger” Test in Swiss MEMPS (Hybrid)

Worldwide NEMP Simulators

IEC 61000-4-32: HEMP Simulator Compendium

China
France
Germany
India
Israel
Italy
Netherlands
Poland
Russia
Sweden
Switzerland
UK
Ukraine

77C/116/CDV 25

7.2.1 China - DM-1200

Terminator-Transmission line - Pulse generator building

General Information

Simulator Type: Guided wave
Termination or Resistive Loading: Output conic section with approximately point resistive load
Major Simulator Dimension(s): 64 m (overall length) 8,4 m (plate spacing)
Test Volume Dimensions: Information not provided

Simulator Input Options

Primary Pulse Power: 1,2-MV Marx generator with pulse shaping network
Repetition Rate: 12 pulses per hour
Low-voltage or CW Test Capability: Not available

Electromagnetic Characteristics
(in test volume unless otherwise noted)

Electric Field Polarization: Vertical
Line Impedance: 180 Ohms (input to terminator)
Wave Impedance: 377 Ohms (HEMP spherical wave)
Peak Electric Field: 120 kV/m
Peak Magnetic Field: 318 A/m
Pulse Rise Time: ~10 ns (10%-90%)
Prepulse: Information not provided
Pulse Width: 200 ns (1/e)
Field Uniformity:
- Uniformity of vertical component --Not Available
- Fall-off of peak field from front to back of test volume --Not Available
- Horizontal components as percent of vertical component --Not Available

Other: Information not provided

Other Information

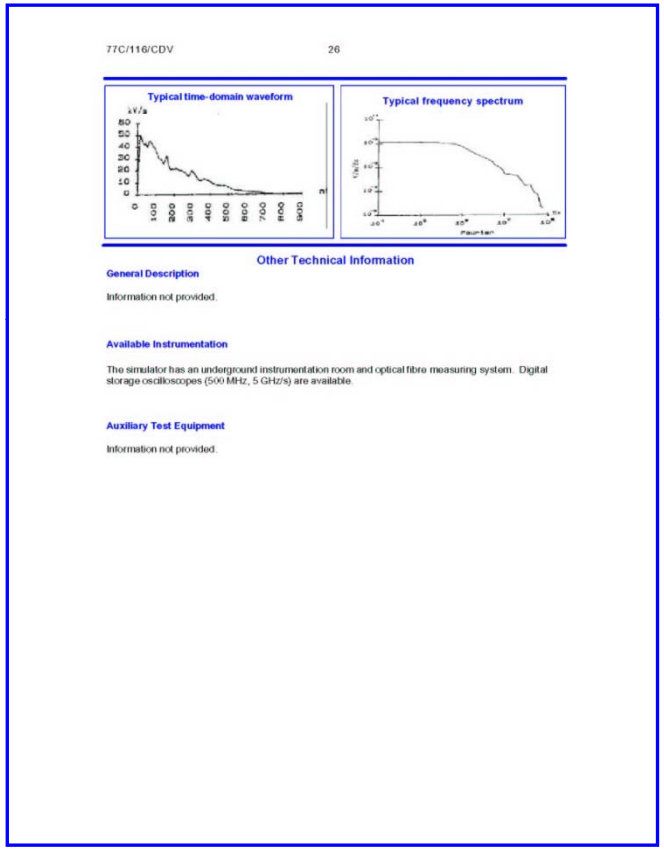
Location: Beijing, China
Owner: Beijing Institute of Electronic System Engineering (BIESE)
Point of Contact: Mr. Pan Hu, China Aerospace Corporation, Second Research Academy, Beijing Institute of Electronic System Engineering, No. 52 Yong Ding Road, P.O. Box 9922, Beijing 100039 Telephone: 86-1-6838-6534 Fax: 86-1-6821-2656

Initial Operation Date: 1986
Status: Operational

Availability

Other Government: Check with point of contact

Industry: Check with point of contact



77C/116/CDV 26

Typical time-domain waveform

Typical frequency spectrum

Other Technical Information

General Description

Information not provided.

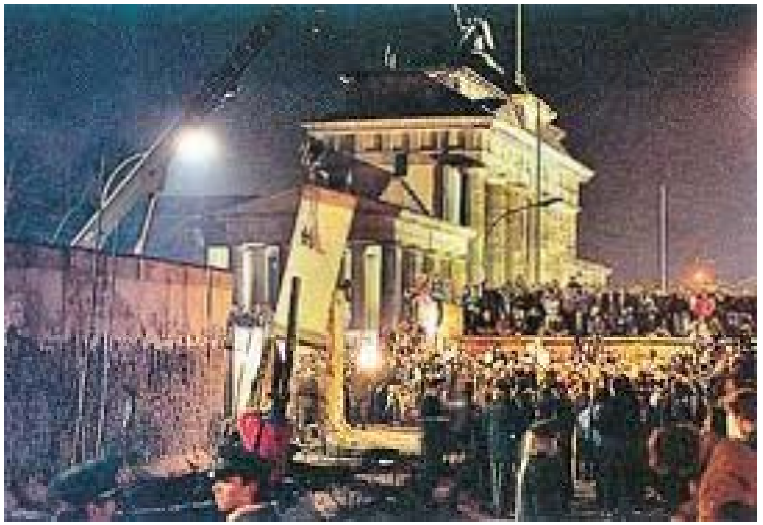
Available Instrumentation

The simulator has an underground instrumentation room and optical fibre measuring system. Digital storage oscilloscopes (500 MHz, 5 GHz/s) are available.

Auxiliary Test Equipment

Information not provided.

Fall of the Berlin Wall - 9 Nov 1989



Dissolution of the Soviet Union → significant impact on HPEM

→ Importance of HEMP began to fade

→ HPM, UWB/SP

1992 **Special Issues in IEEE EMC Transactions on HPM, D. V. Giri as the Guest Editor**

HPEM technical sessions in various meetings
URSI Statement on NEMP and associated effects

1990 **URSI Commission E, forms a HPEM working group**
1993 **IEC issues 61000-2-9 - Radiated HEMP Env.**

1994 **EUROEM Conference in Bordeaux, France**

The HPEM environment can be:

- *a single pulse with many cycles of a single frequency (an intense narrowband signal that may have some frequency agility),*
- *a burst containing many pulses, with each pulse containing many cycles of a single frequency,*
- *an ultra-wideband transient pulse (spectral content from 10s of MHz to several GHz),*
- *a burst of many ultra-wideband transient pulses, and*
- *radiated or conducted.*

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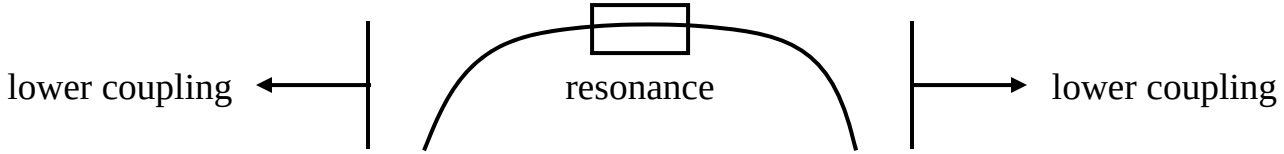
Frequency Range for Radiated HPEM

frequency	200 MHz	→	5 GHz
wavelength	150 cm	→	6 cm



- It is possible to produce ~10^{-6} V/m/Hz
  ~ flat spectrum throughout this range!
  ~ 100s of m→ km ranges, 2m antenna

- This is roughly 3 decades below NEMP spectrum

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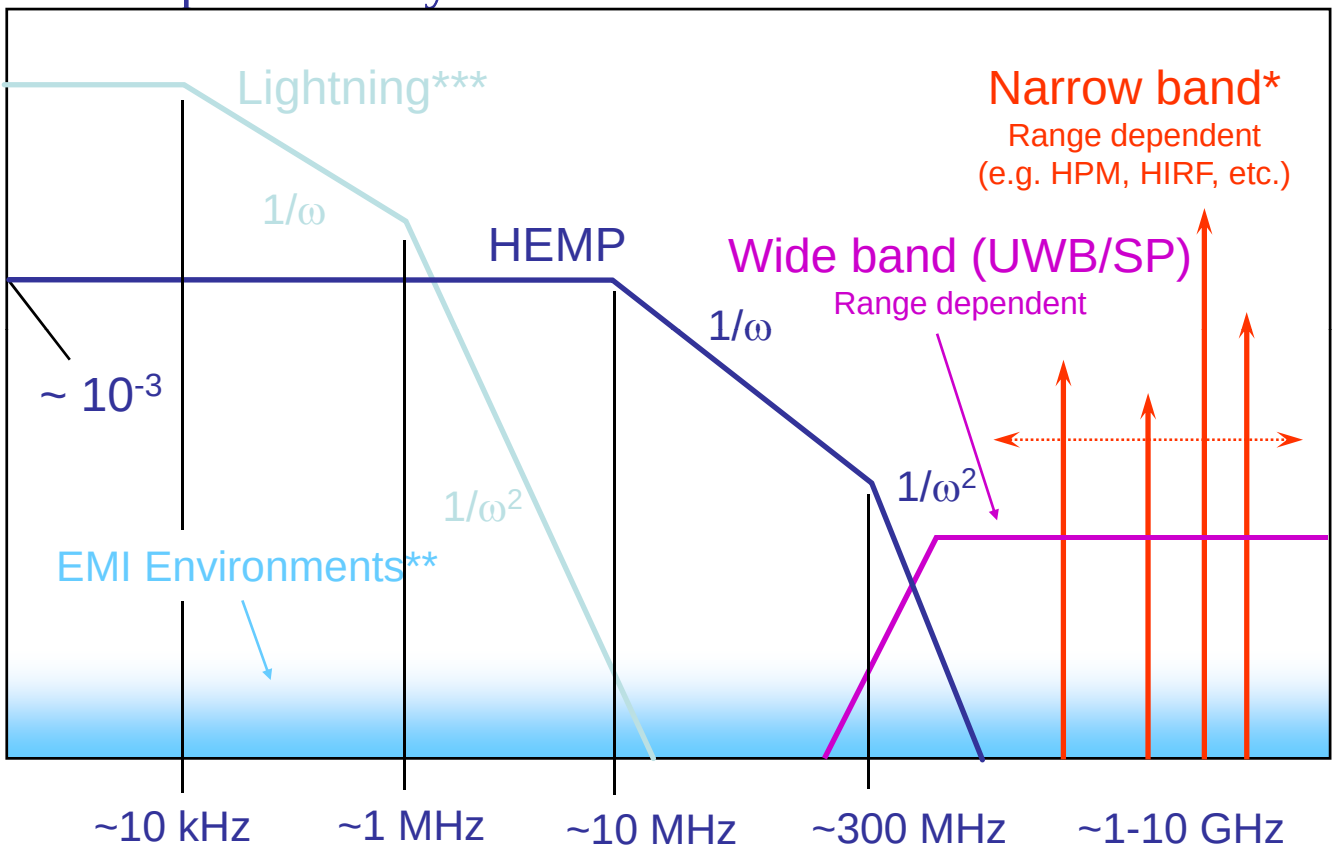
Frequency Range of 100 MHz to 5 GHz

- **There could be deliberate antennas, which provide a path into the system (front door coupling paths)**
- **Typical apertures, slots, holes and hatch openings have their resonance in this frequency regime (inadvertent or back-door coupling paths)**
- **Typical rivet spacing at the junction of two metallic surfaces at the skin level are about a quarter to full wavelength in this frequency regime**
- **Physical dimensions of circuit boxes are themselves resonant in this frequency regime**
- **The interior coupling paths e.g., transmission lines, cables are at a height above the ground plane (inner surface of the outer skin of an aircraft), that is roughly a quarter to full wavelength in this frequency regime.**

MANY FACES OF HPEM- a notional view

First presented by Giri and Kaelin in AMEREM-1996

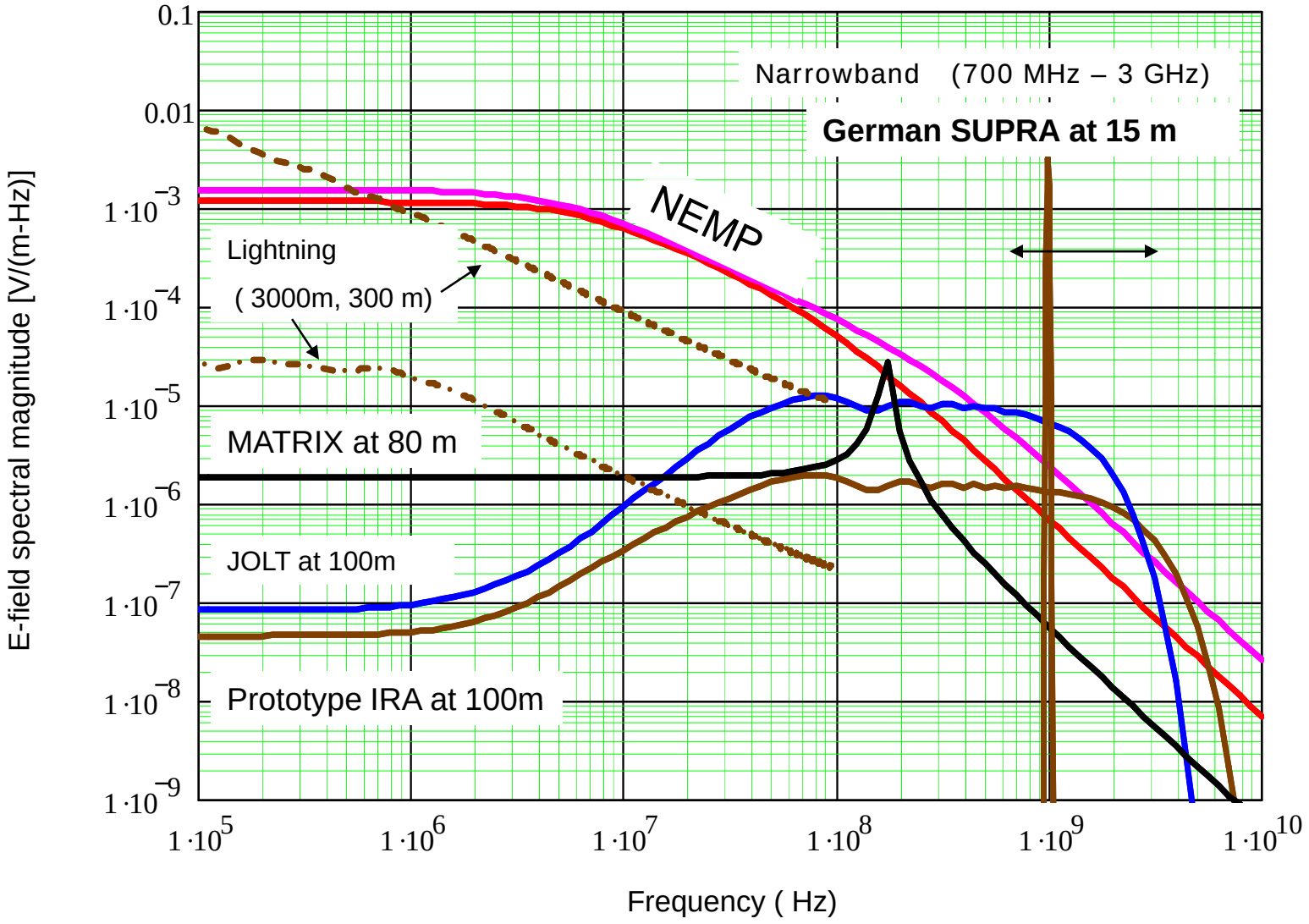


* narrow band extending from ~0.5 to ~5 GHz

** not necessarily HPEM

*** significant spectral components up to ~10 MHz depending on range and application

Composite HPEM Waveforms 2006



With all these High-Power Environments

→ we needed a way of classifying them

→ settled on bandwidth as a basis

Published in:

1) IEEE EMC Transactions Aug 2004
Giri and Tesche, Special Issue on HPEM Edited by Dr. W. Radasky

2) IEC 61000-2-13 as a Standard

Classification of HP Environments

Benefit: Standardization of Environments

1. DARPA Definition → 3 bands

- Narrow band signal → percentage bandwidth < 1% (ex: AM radio signal)
- Moderate bandwidth signal → percentage bandwidth ~ 1 to 25 % (ex: TV signal)
- Ultra wideband signal → percentage bandwidth > 25% (ex: IRAs)

OSD/DARPA, Ultra-Wideband Radar Review Panel, Assessment of Ultra-Wideband Technology, 1990

2. FCC Definition of UWB: signal with a pbw > 20% or an absolute bandwidth > 500 MHz

3. Considering Emerging Technologies with band ratio of 100 → 4 bands

	Narrow	Moderate or Meso	Ultra Moderate sub-hyper	Hyper
with pbw	< 1 %	1 to 100%	100 to 163.64	163.64 to 200%
or band ratio	< 1.01	1.01 to 3	3 to 10	> 10

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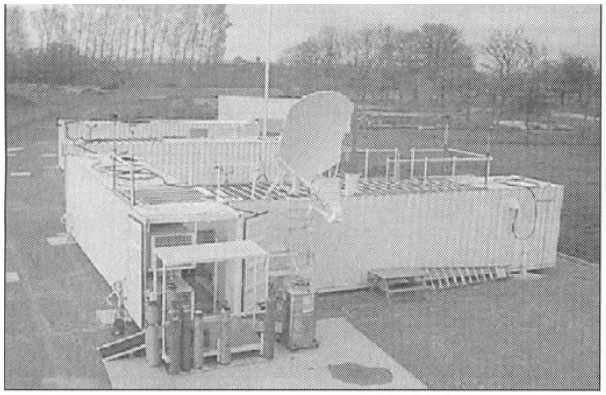
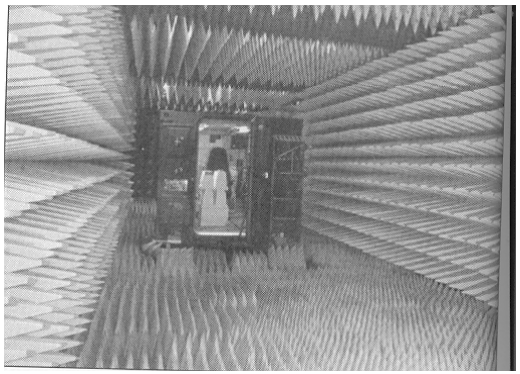
4 Examples of Narrowband HPM Systems

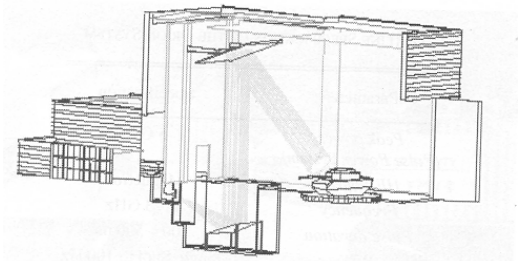
MTF - Sweden



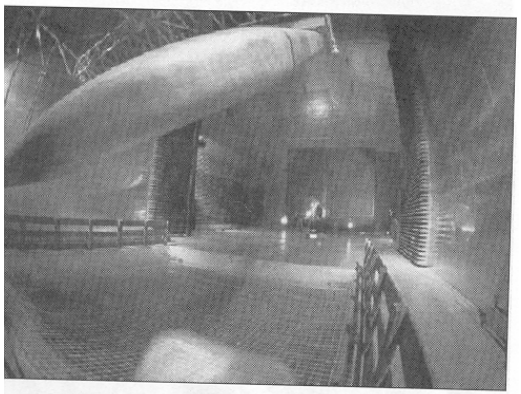
ORION- U. K.



SUPRA – Germany



5. HYPERION.



An airplane tested with HYPERION.

HYPERION -

CEG France

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Major Characteristics of the 4 European Narrowband HPM Systems

Feature	MTF SWEDEN	ORION U.K.	Hyperion FRANCE	Supra GERMANY
RF Source	Conventional Tubes	Relativistic Magnetrons	Relativistic Magnetron & Reltrons	Reltrons
Frequency	1.3, 2.86, 5.71, 9.30 and 15 GHz	1 – 3 GHz	1.3-1.8 GHz (Magnetron) 2.4 – 3.0 GHz (Magnetron) 0.72 – 1.44 GHz(Reltron)	0.675 – 1.44 GHz
Max. Power	25, 20, 5, 1, 0.25 MW as a function of frequency	350 MW of microwave power ; 5 GW pulse power 500 kV; 50Ohm	---	400 MW – 200 MW
Max. PRF	1000,1000,1000 1000 and 2100 Hz	Single shot to 100 Hz	----- (Magnetron) 1 Hz (Reltron)	10 Hz
Max. Pulse Duration	5, 5, 5,3,8 & 0.53 μs	500 ns	100 ns Magnetron 200 ns Reltron	> 300 ns
Field Level	--- L-band 30 kV/m at 15 m S-band 30 kV/m at 15 m	---	40 kV/m (with Reltron) 60 kV/m (with Magnetron)	70 kV/m at 15 m

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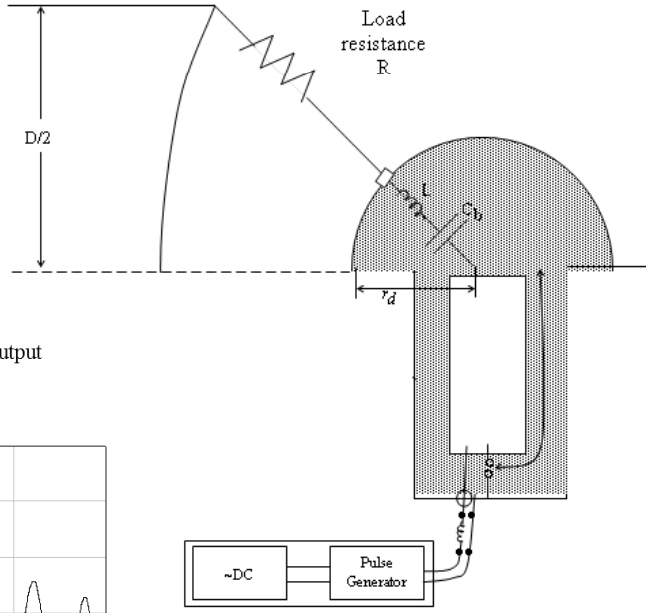
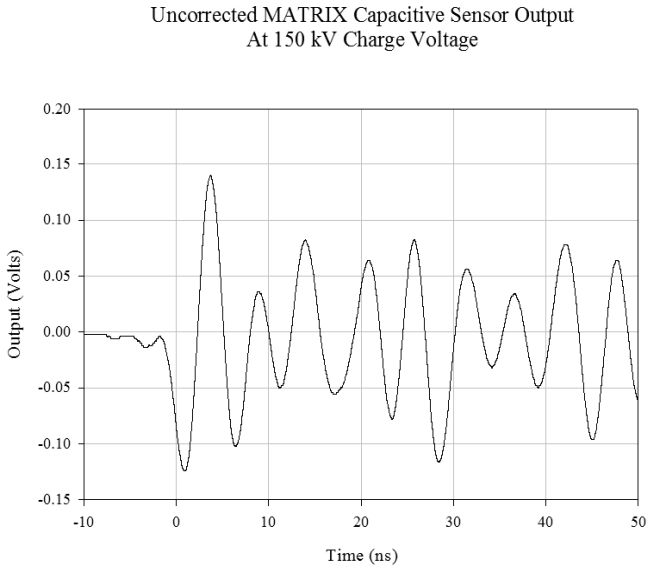
Examples of Moderate/ Meso - Band Systems

1 % < pbw ≤ 100 % or 1.01 < br ≤ 3

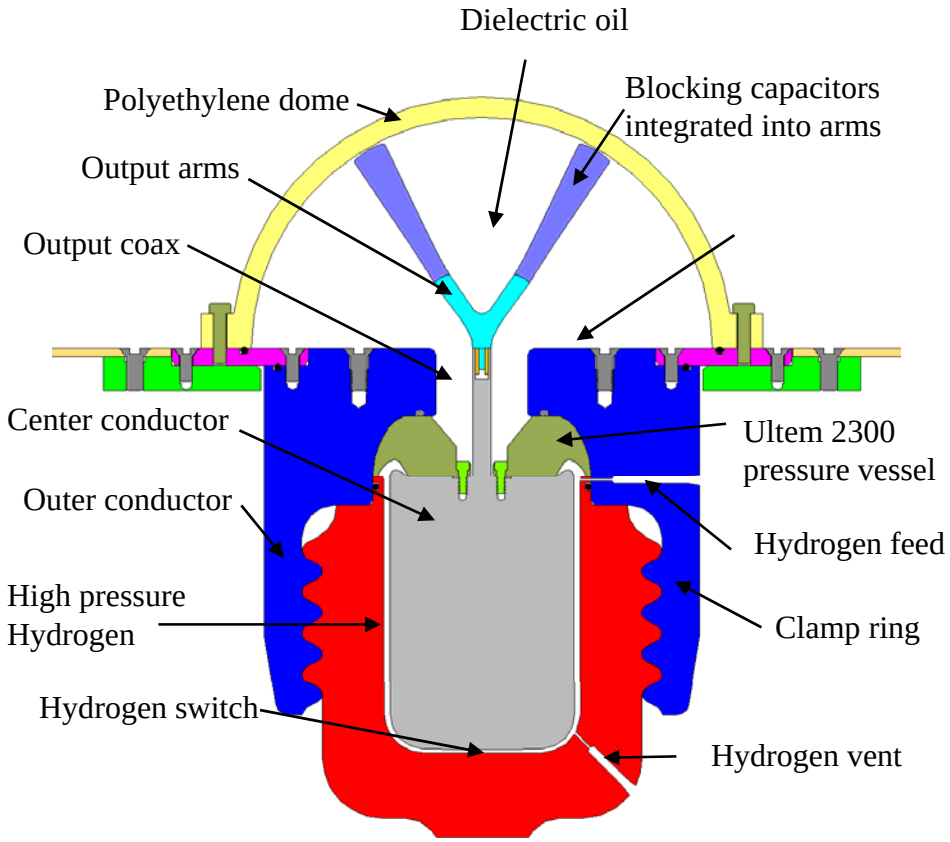
- The MATRIX





MATRIX Switched Oscillator Overview

- Coaxial transmission line operates as a ¼ wave oscillator.
- Designed to oscillate at 184 MHz.
- Designed for Q = 20 when operated into 100 Ω load.
- High pressure Hydrogen insulated.
- Designed to maximize strength by placing Ultem 2300 (weakest material) under compression while pressurized.



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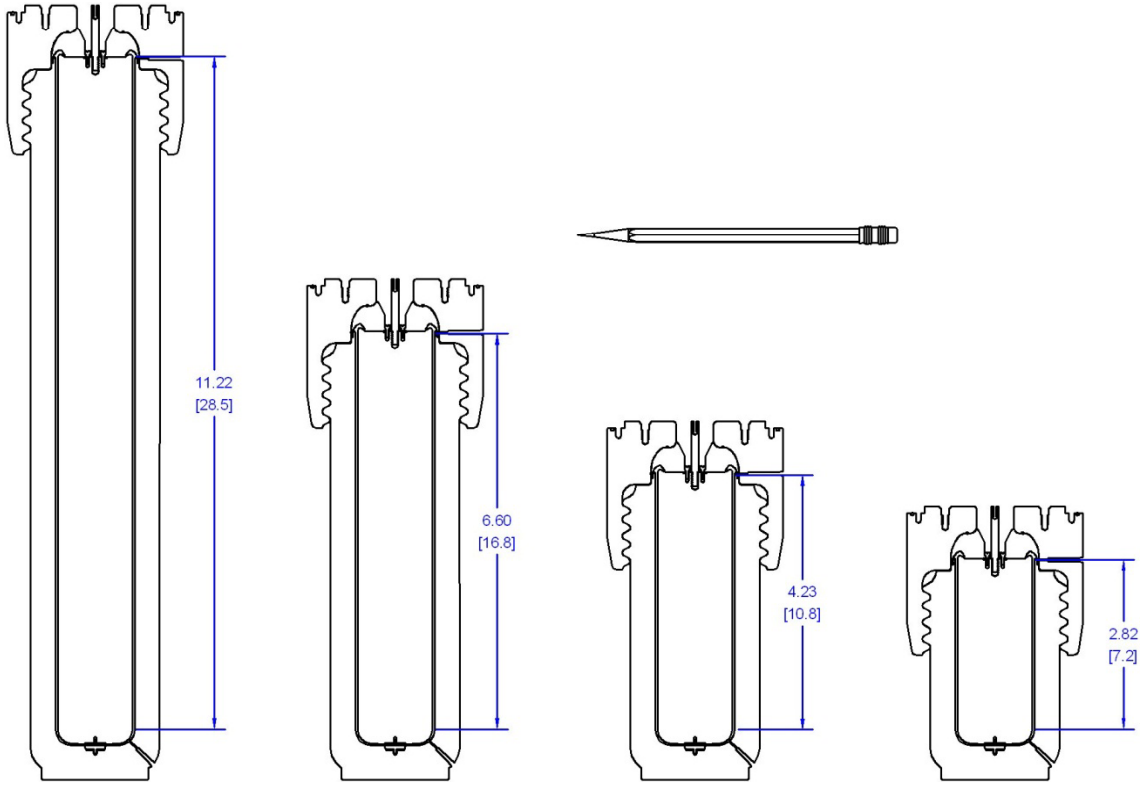
Coaxial Section Lengths for each Frequency

Oscillator Coaxes	T (ns)	L (cm)
200 MHz	0.95	28.5
300 MHz	0.56	16.8
400 MHz	0.36	10.8
500 MHz	0.24	7.2

1.5 GHz and 2 GHz
Have been built



500 MHz Switched Oscillator

feeding a helical antenna

Ultra-moderate Band Systems

(100 % < *pbw* < 163.64 %) or (3 < *br* < 10)

- **Some of the H-series systems (for example H-2) built at the Air Force Research Laboratory, Kirtland AFB, NM have bandwidths that qualify them as Ultra moderate systems.**

- **Specifically, the H-2 generates a 300 kV/250 ps/~ 2 ns pulse feeding a TEM horn that radiates a pulse of 43 kV/m at a distance of 10m (r E peak ~ 430 kV)**

- **A second example is the THOR system with a 1 MV pulse producing a peak electric field of 68 kV/m at 10m(r E peak = 680 kV) with a FWHM of 400 ps. The bandwidth is from 200 MHz to 1 GHz or a**

  ***br* ~ 5 .**

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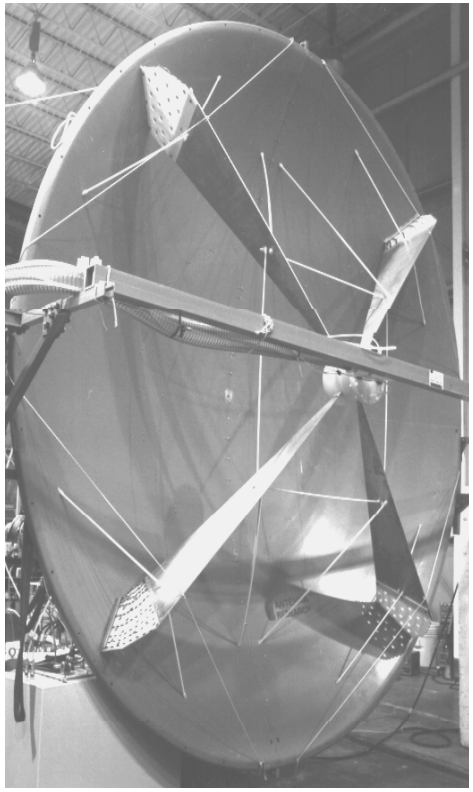
Hyperband Source/Antenna Systems) Full IRAs

range of diameters (10 cm to 3.67m) (4 in to 12 ft)



3.67 m (12 ft)

AFRL-USA

1.83 m (6 ft)
AFRL-USA

23 cm Pro-Tech

1.8 m
Switzerland

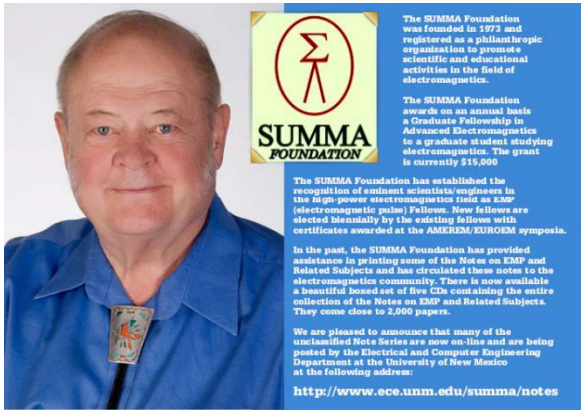
10 cm (4 inches)
Pro-Tech

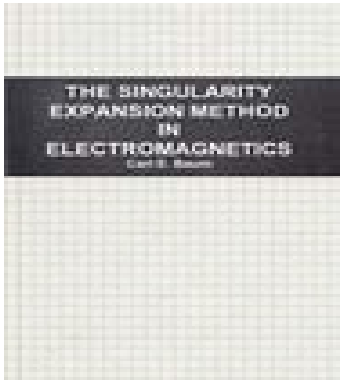
90 cm TNO & Munster

Photograph of JOLT system

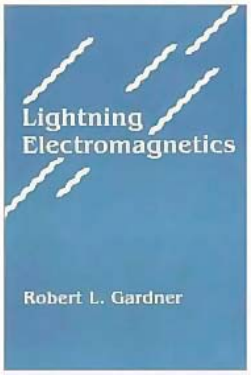
Prsented in EUROEM 2004 in Magdeburg, Germany

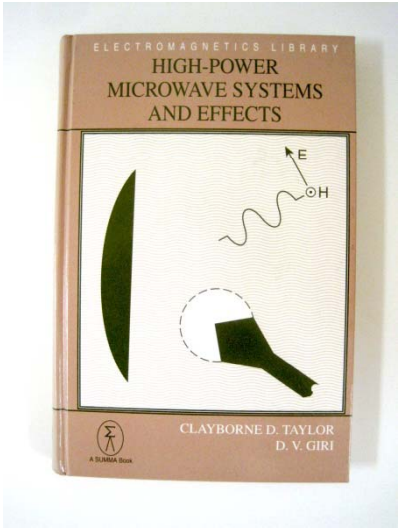
Half IRA Radiating an Impulse-Like Waveform


SUMMA
FOUNDATION
The SUMMA Foundation was founded in 1973 and registered as a philanthropic organization to promote scientific and educational activities in the field of electromagnetics.
The SUMMA Foundation awards on an annual basis a Graduate Fellowship in Advanced Electromagnetics to a graduate student studying electromagnetics. The grant is currently $15,000
The SUMMA Foundation has established the recognition of eminent scientists/engineers in the high-power electromagnetics field as EMP (electromagnetic pulse) Fellows. New fellows are elected biennially by the existing fellows with certificates awarded at the AMEREM/EUROEM symposia.
In the past, the SUMMA Foundation has provided assistance in printing some of the Notes on EMP and Related Subjects and has circulated these notes to the electromagnetics community. There is now available a beautiful boxed set of five CDs containing the entire collection of the Notes on EMP and Related Subjects. They come close to 2,000 papers.
We are pleased to announce that many of the unclassified Note Series are now on-line and are being posted by the Electrical and Computer Engineering Department at the University of New Mexico at the following address:
http://www.ece.unm.edu/summa/notes


THE SINGULARITY EXPANSION METHOD IN ELECTROMAGNETICS

HIGH-POWER MICROWAVE SOURCES AND TECHNOLOGIES


Lightning Electromagnetics
Robert L. Gardner


ELECTROMAGNETICS LIBRARY
HIGH-POWER MICROWAVE SYSTEMS AND EFFECTS
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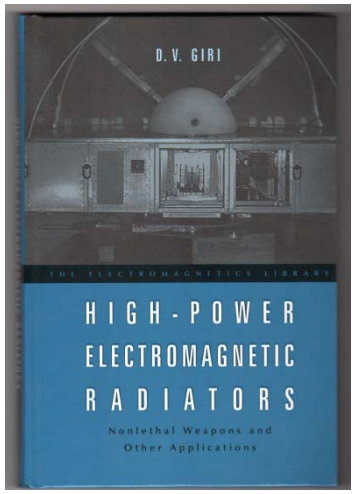
D. V. GIRI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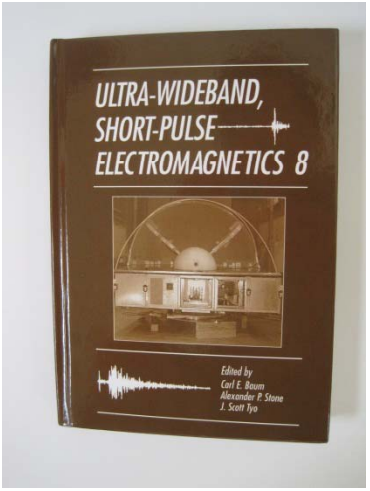
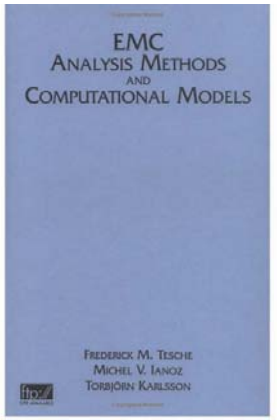
HIGH-POWER ELECTROMAGNETIC RADIATORS
Nonlethal Weapons and Other Applications


ULTRA-WIDEBAND, SHORT-PULSE ELECTROMAGNETICS 8
Edited by
Carl E. Baum
Alexander P. Stone
J. Scott Tyo


EMC
ANALYSIS METHODS AND COMPUTATIONAL MODELS
FREDERICK M. TESCHE
MICHEL V. IANOZ
TORBJÖRN KARLSSON

HPEM

Prime Focus of this Conference

- **E**lectromagnetic **E**nvironments
- **E**ffects
- **P**rotection

→ **EEEP** Chart or **E^3P** Chart

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Electromagnetic Environments, Effects and Protection

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ANTI-ELECTRONICS

Electronic System Example

MILITARY	CIVILIAN
Aircraft, Missiles, Ships, Satellites, Tanks...	Aircraft, Computer, Power, Communication, Infrastructure...

ANTI-PERSONNEL

~100 GHz or mm-waves

AREA DENIAL TECHNOLOGY
HPEM-Personnel
HPEM-P

ELECTROMAGNETIC ENVIRONMENTS

Intentional Electromagnetic Interfering Signals (IEMIS)
or High-Power Electromagnetic (HPEM) Signals

100 MHz to ~5 GHz

Example System	HIGH-POWER MICROWAVES	DAMPED SINUSOIDS	SHORT PULSE	SHORT PULSE
	Ex: MTF, ORION, HYPERION, SUPRA	Ex: MATRIX	Ex: THOR, H-Series	Ex: HEMP (DC to 500 MHz) 12' Prototype IRA Syst. 6' IRA System, JOLT etc.
	Center Frequency 500 MHz to 5 GHz	Center Frequency 100 MHz to 500 MHz	Less than 1 Decade of Frequencies	More than 1 Decade of Frequencies
	Percent Bandwidth (pbw) pbw < 1%	Percent Bandwidth (pbw) 1% ≤ pbw < 100%	Percent Bandwidth (pbw) 100% ≤ pbw < 163.4%	Percent Bandwidth (pbw) 163.64% ≤ pbw < 200%
	Bandratio (br) br < 1.010	Bandratio (br) 1.01 ≤ br < 3	Bandratio (br) 3 ≤ br < 10	Bandratio (br) br ≥10
	HPEM - Narrow Band	HPEM - Moderate Band	HPEM - Ultra Moder. Band	HPEM - Hyper Band
	HPEM - N	**HPEM - M**	**HPEM - U**	**HPEM - H**

Lightning Discharge (DC to 100 MHz)
and
Operational Equipment
EMI (DC to 40 GHz)

- Inter System
- Intra System

ELECTROMAGNETIC EFFECTS

4 LEVELS & Consequences

1. **NOISE (front door)** ~ 1 V/m harmless
2. **FALSE INFORMATION** (front door) ~ 10 V/m can be critical
3. **TRANSIENT UPSET** (back door) ~100's V/m System may recover
4. **PERMANENT DAMAGE** (back door) ~1000's V/m can be critical

PROTECTION AND HARDENING to Certain Level, Often Defined by Standards

From **IEMIS** or **HPEM**

From Natural or Operating Environment **EMI**

GOAL

☑ Protected **System** or Electromagnetic Compatibility **(EMC)**

upto desired levels which are often prescribed by Standards

Radio Spectrum

ULF	SLF	ELF	VLF	LF	MF	HF	VHF	UHF	SHF	EHF	MILLIMETER
3Hz	30Hz	0.3kHz	3kHz	30kHz	300kHz	3MHz	30MHz	300MHz	3GHz	30GHz	300GHz	3THz

ULF - Geophysical prospecting
SLF - Submarine communication
ELF - Telephone, audio

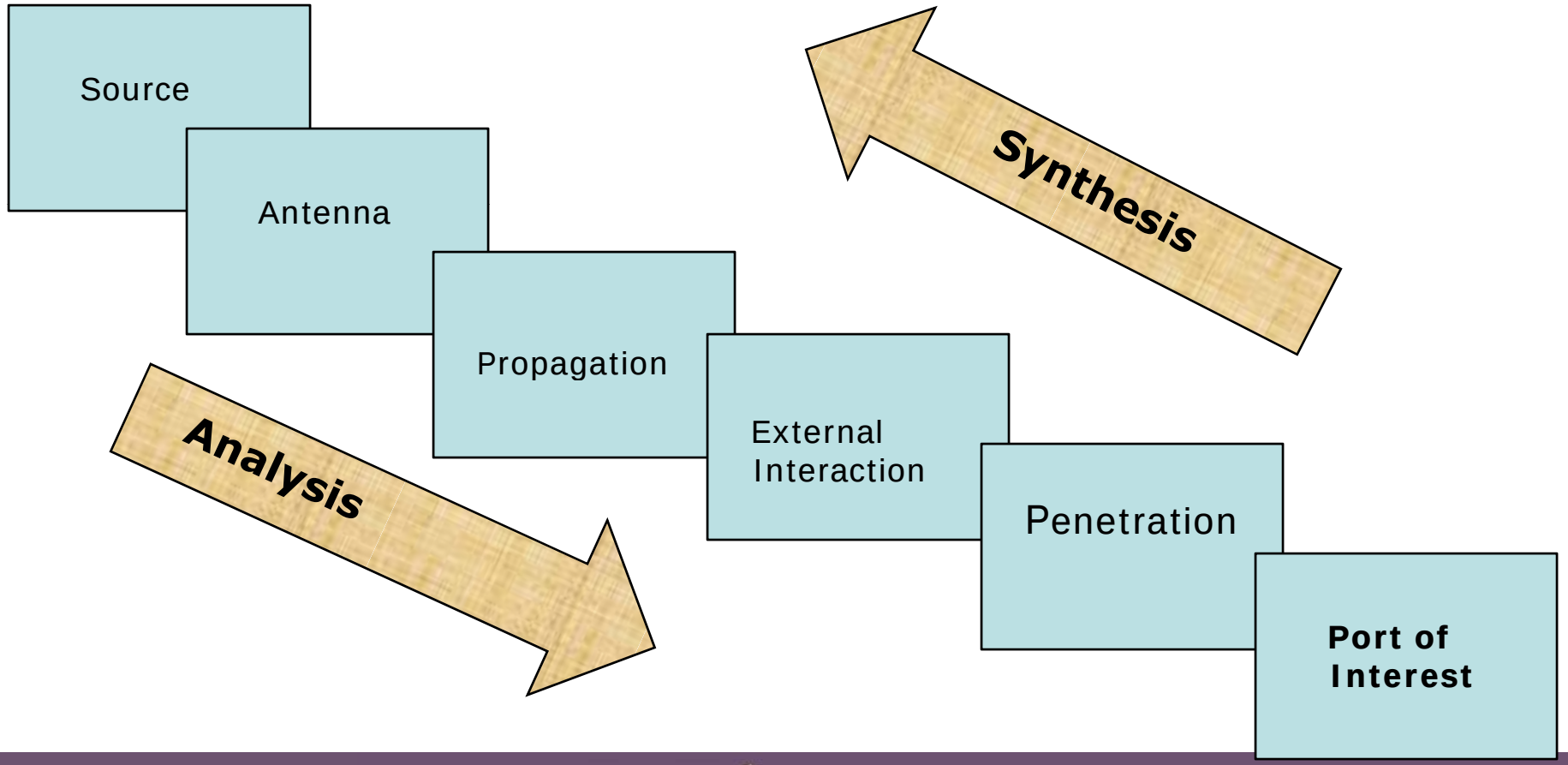
VLF - Navigation
LF - Radio beacons for aircraft, standard time and frequency signal
MF - Radio broadcasting (AM radio), maritime communications

HF - Aeronautical communication, short wave communication
VHF - TV broadcasting, air traffic control, mobile communication
UHF - Cell phone, taxi radio, radar

SHF - Satellite communication, radar, astronomy
EHF - Remote sensing, satellite communication, radar
MILLIMETER - Astronomy, meteorology, area denial technology

Source to Target – Target to Source

C. E. Baum, "Maximization of Electromagnetic Response at a Distance," *C.E. Baum Sensor and Simulation Notes, 312, 1988.* *Also in IEEE EMC Spécial Issue on HPM August 1992*



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Getting Back to the Histoy…

1994 **EUROEM Conference in Bourdeaux, France**

1995 **High-Power Short Pulse (IRA) technology development**

1996 **Russian Scientists participate in AMEREM 1996, Albuquerque, NM**
comment: "US NEMP programs were possible because of them"

1999 **URSI Statement on IEMI**

Entering 21st Century

2004 **U.S. Congressional Committee publishes its first Report on EMP**
W.R. Graham (Chairman, EMP Commission) et al., "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack," Volume 1, Executive Report,
Special Issue on IEMI in IEEE Transactions on EMC

2008 **EMP Commission report on threats to Critical Infrastructures**
W.R. Graham (Chairman, EMP Commission) et al., "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack – Critical National Infrastructures", April 2008.

Looking Ahead…

“Prediction is very difficult, especially about the future” ,,,,, Niels Bohr

- répartie (Einstein and Bohr)

“The future is like a corridor into which we can see only by the light coming from behind.”

…..Anonymous..

Some thoughts

- ✓ **Compact HPEM source/antenna systems are available**
- ✓ **Developments in compact pulse-power technologies driving conventional and newer RF devices will lead to improved and more powerful source/ antenna systems.**
- ✓ **An EMP attack is an example of RF terrorism by rogue countries and non-state actors, and the national infrastructure can be at risk.**
- ✓ **Infrastructure is a hyper system or a system of systems such as electric power, telecommunication, banking & finance, energy, transportation, food, water, emergency, space, and Government**

.

- ✓ **In addition, cyber threats from hostile governments, terrorist groups and disgruntled employees are on the increase as well.**

- ✓ **It is prudent for civilized societies to asses such threats and take pro-active and precautionary actions.**

Nine Eleven as an example,
if someone had foreseen a threat scenario wherein commercial airliners can be turned into missiles by hijackers, perhaps Nine-Eleven could have been avoided.
Pro-active step would have been to install bullet-proof cockpit doors to deny entry to unauthorized persons

The first decade of the 21st century has seen real and anecdotal evidence of RF Terrorism and IEMI

→ Leads to Dr. Frank Sabbath's talk